Two-dimensional metal-insulator transition and in-plane magnetoresistance in a high mobility strained Si quantum well

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(Dated: February 2, 2008)

The apparent metal-insulator transition is observed in a high quality two-dimensional electron system (2DES) in the strained Si quantum well of a $Si/Si_{1-x}Ge_x$ heterostructure with mobility $\mu = 1.9 \times 10^5$ cm^2/Vs at density $n = 1.45 \times 10^{11}$ cm^{-2}. The critical density, at which the thermal coefficient of low T resistivity changes sign, is $\sim 0.32 \times 10^{11}$ cm^{-2}, so far the lowest observed in the Si 2D systems. In-plane magnetoresistance study was carried out in the higher density range where the 2DES shows the metallic-like behavior. It is observed that the in-plane magnetoresistance first increases as $\sim B_{ip}^2$ and then saturates to a finite value $\rho(B_c)$ for $B_{ip} > B_c$. The full spin-polarization field B_c decreases monotonically with n but appears to saturate to a finite value as n approaches zero. Furthermore, $\rho(B_c)/\rho(0) \sim 1.8$ for all the densities ranging from 0.35×10^{11} to 1.45×10^{11} cm^{-2} and, when plotted versus B_{ip}/B_c, collapses onto a single curve.

The two-dimensional (2D) metal-to-insulator transition (MIT) has been of great current interests.[1,2] According to the well-established scaling theory,[3] any amount of disorder in a non-interacting 2D electron system (2DES) will localize the carriers at zero temperature (T) and zero magnetic (B) field, and the ground state of the 2DES is an insulator, whose conductivity logarithmically goes to zero as $T \to 0$. Recent experimental studies in high quality dilute 2D systems where the electron-electron ($e-e$) interaction is large, however, have shown the existence of a metallic-like state and an apparent metal-insulator transition. There, the magnitude of the 2DES resistivity (ρ) undergoes a change from decreasing with decreasing T, ($d\rho/dT > 0$), a metallic behavior, to increasing with decreasing T, ($d\rho/dT < 0$), an insulating behavior, at a critical density n_c.

One of the fundamental questions in this apparent MIT problem is the nature of the metallic state[4] and its response to a pure in-plane magnetic field (B_{ip}).[5,6,7,8,9,10,11,12,13] It is observed that in conventional clean Si-MOSFET's the in-plane magnetoresistance (MR) of the 2DES, $\rho(B_{ip})$, first increases as B_{ip}^2 at low B_{ip}. After a critical B field B_c, which has been identified as the full spin polarization B field for the 2DES,[7,8,9] the in-plane MR saturates to a constant value $\rho(B_c)$.[14] The enhancement of $\rho(B_{ip})$ under high in-plane B field in this 2DES is attributed to the reduction of screening of charged impurities in a Fermi liquid, caused by the loss of spin degeneracy,[15,16,17] and a ratio of $\rho(B_c)/\rho(0) = 4$ or ~ 1.2 is expected when the background impurity scattering[15] or the remote ionized impurity scattering[17] dominates. Thus, it is surprising that close to the critical density n_c, the enhancement can be as large as several orders of magnitude.[1,2,5,7,8,10,11] Furthermore, it has been shown that under B_{ip} the metallic state is suppressed, and completely destroyed for $n < 1.5n_c$. A recent study has demonstrated that the disappearance of the positive $d\rho/dT$ in large B_{ip} is due to a competition between weak localization and other mechanisms, such as screening.[13]

So far, most of the large number of experiments on 2D MIT in the Si 2DES are carried out using the so-called clean Si-MOSFET structures with peak electron mobility μ of $\sim 4 \times 10^4$ cm^2/Vs. In recent years, the 2DES in the high quality strained Si quantum well (QW) in $Si/SiGe$ heterostructures has emerged as a promising Si system to study strong electron-electron interaction physics, *e.g.*, the fractional quantum Hall effect.[18] Due to modulation doping and smooth interface, electron mobility at least 2-3 times better than that in the cleanest Si-MOSFET's, can be routinely achieved.

In this communication, we report experimental results on the apparent metal-insulator transition in a high quality 2DES in the strained Si quantum well of a $Si/Si_{1-x}Ge_x$ heterostructure. The critical density is found to be $\sim 0.32 \times 10^{11}$ cm^{-2}, much smaller than that observed in clean Si-MOSFET's, where $n_c \sim 0.8 \times 10^{11}$ cm^{-2}. The in-plane magnetoresistivity ($\rho(B_{ip})$) measurements were carried out in the density regime where the 2DES shows the metallic-like behavior at $B = 0$. It is observed that $\rho(B_{ip})$ first increases as $\sim B_{ip}^2$ and then saturates to a finite value $\rho(B_c)$ for $B > B_c$. The full spin-polarization field B_c decreases monotonically with n but appears to saturate to a finite value as n approaches zero. Furthermore, $\rho(B_c)/\rho(0) \sim 1.8$ for all the densities ranging from 0.35×10^{11} to 1.45×10^{11} cm^{-2} and, when plotted versus B_{ip}/B_c, collapses onto a single curve.

The starting specimen is an MBE-grown $Si/S_{1-x}Ge_x$ heterostructure, with a 15 nm wide strained Si quantum well. Details of the growth structure is given in Ref. [19]. A field-effect transistor type device was then fabricated.[20] At $T \sim 300$ mK and zero gate voltage, the 2DES has a density $n = 1.45 \times 10^{11}$ cm^{-2} and mobility $\mu = 190,000$ cm^2/Vs. Standard low-frequency ($\sim$ 7Hz) lock-in techniques were used to measure the 2D transport coefficients.

We show in Figure 1 the magnetoresistivity ρ_{xx} and Hall resistance ρ_{xy} at $n = 0.42 \times 10^{11}$ cm^{-2}. The appearance

of strong integer quantum Hall effect (IQHE) states at Landau level fillings $\nu = 1, 2$, as well as at $\nu = 4$ demonstrate high quality of the 2DES.

In Figure 2, we show the temperature dependence of ρ, the zero B resistivity, at selected densities. At $n \geq 0.63 \times 10^{11}$ cm^{-2}, ρ monotonically decreases with decreasing temperature. Below 0.3×10^{11} cm^{-2}, ρ increases rapidly with decreasing T and the 2DES is in the insulating regime. The critical density n_c, at which the thermal coefficient of low T resistivity changes sign, is 0.32×10^{11} cm^{-2}. We emphasize that it is by far the lowest n_c obtained in the Si based 2D systems. In the so-called transition regime between $0.35 \times 10^{11} \leq n \leq 0.55 \times 10^{11}$ cm^{-2}, ρ first increases with decreasing T, reaches a maximum, and then decreases with continuously decreasing temperature.

One of the fundamental questions in this apparent MIT problem is the in-plane magnetoresistivity $\rho(B_{ip})$.[5,6,7,8,9,10,11,12,13] In Figure 3(a), $\rho(B_{ip})$ is plotted for several densities. Like in Si-MOSFET's, $\rho(B_{ip})$ first increases as $\sim B_{ip}^2$. After a critical B field B_c, it saturates to a roughly constant value, $\rho(B_c)$. In Figure 3(b), $\rho(B_{ip})/\rho(0)$ is plotted versus B_{ip}/B_c. It is clear that in this large density range, from 0.35×10^{11} to 1.45×10^{11} cm^{-2}, $\rho(B_{ip})/\rho(0)$ collapse onto a single curve, and $\rho(B_c)/\rho(0) \sim 1.8$ for all the densities.

B_c in Figure 3(a) represents the B field beyond which electrons become fully spin-polarized.[7,8,9] In Figure 3(c), we plot B_c as a function of n. We also include the data obtained by Okamoto *et al*,[21] measured at densities $n > 1 \times 10^{11}$ cm^{-2}. Results from two experiments are in good agreement with each other. At high n's, B_c decreases roughly linearly with n. In fact, for $n > 0.8 \times 10^{11}$ cm^{-2}, $B_c = -1.38 + 5.55 \times n$. The decreasing rate slows down at lower electron densities and deviates from that of the linear dependence. B_c appears to approach a finite value as $n \rightarrow 0$.

In Figure 4, we show the temperature dependence of the in-plane MR at three different densities. At the high density of $n = 0.515 \times 10^{11}$ cm^{-2}, the 2DES remains metallic even at $B_{ip} = 7$ T, much higher than the critical B field of $B_c \sim 2$ T. At the intermediate density of $n = 0.38 \times 10^{11}$ cm^{-2}, the 2DES shows metallic behavior at small B_{ip}, becomes insulating at $B_{ip} \sim 1.5$ T, and then re-enters into the metallic phase at higher B_{ip}. When n is further reduced to $n = 0.35 \times 10^{11}$ cm^{-2}, the in-plane field simply destroys the zero B metallic phase, and the 2DES becomes insulating at $B_{ip} > \;\sim 1$ T.

The observed critical density $n_c = 0.32 \times 10^{11}$ cm^{-2} is about one order of magnitude smaller than the n_c observed in lower quality $SiGe$ systems (for example, $n_c = 2.35 \times 10^{11}$ cm^{-2} in Ref. [20] with the highest 2DES mobility of $\mu = 7.5 \times 10^4$ cm^2/Vs, and $n_c = 4.05 \times 10^{11}$ cm^{-2} in Ref. [22] with the highest mobility $\mu = 6.0 \times 10^4$ cm^2/Vs) and $\sim$ 2-3 times smaller than that in clean Si-MOSFET's, where $n_c \sim 0.8 \times 10^{11}$ cm^{-2}.[1] Thus, our result demonstrates that n_c in the Si systems also decreases as the sample quality increases, consistent with previous observations in the $GaAs$ systems.[23] Furthermore, at the critical density of $n_c = 0.32 \times 10^{11}$ cm^{-2}, the dimensionless $e-e$ interaction parameter $r_s = (\pi/n)^{1/2}(e/h)^2(m^*/\epsilon\epsilon_0)$ is 10, where $m^* = 0.2m_e$ is the electron band mass and $\epsilon = 11.7$ is the dielectric constant for strained Si, and other parameters have their usual meanings. This is the largest critical r_s so far obtained in the Si based 2DES's. We note here that this number, however, is only slightly higher than that ($r_s \sim 9.3$ at $n_c = 0.8 \times 10^{11}$ cm^{-2}) reported in clean Si-MOSFET's. But, as pointed by Okamoto *et al*,[21] in previous calculations in clean Si-MOSFET's, the critical r_s value was over estimated due to the use of an average relative dielectric constant of silicon and SiO_2, $\epsilon_{av} = 7.7$, in the calculation of $r_s = (\pi/n)^{1/2}(e/h)^2(m^*/\epsilon_{av}\epsilon_0)$. Considering that the average distance of the 2D electrons from the Si/SiO_2 interface is comparable to the average distance between two electrons, the realistic ϵ should be larger than 7.7,[21] thus reducing the critical r_s to ~ 8 in clean Si-MOSFET's.

The observed enhancement of the $\rho(B_{ip})$ under high in-plane B field can be explained by the reduction of screening of charged impurities in a Fermi liquid, caused by the loss of spin degeneracy.[15,16,17] It has been shown that, when the background impurity scattering dominates, a ratio of $\rho(B_c)/\rho(0) = 4$ is expected.[15] On the other hand, when the remote ionized impurity scattering prevails, this ratio is reduced to ~ 1.2.[17] The ratio of $\rho(B_c)/\rho(0) \sim 1.8$ in our measurements sits between these two limits and is closer to 1.2, indicating that the dominating scattering mechanism at low temperatures is from remote ionized impurities. This is consistent with our sample growth structure, where the doping layer is 150 $\AA$ away from the 2D electron channel. The slightly higher ratio than 1.2 is probably related to the strain field, which can act as background scattering centers. What is surprising in our results is that in a wide density range the enhancement of $\rho(B_c)/\rho(0)$ is the same, even at the density of $n = 0.35 \times 10^{11}$ cm^{-2}, which is only 10% higher than the critical density of $n_c = 0.32 \times 10^{11}$ cm^{-2}. On the contrary, in high quality Si-MOSFET's, while $\rho(B_c)/\rho(0) \sim 2.2$ at very high densities,[24] the enhancement is much higher when n is close to n_c, *e.g.*, $\rho(B_c)/\rho(0) \sim 10$ at 0.89×10^{11} cm^{-2},[8] which also is about 10% higher than the n_c of $\sim 0.8 \times 10^{11}$ cm^{-2}. We speculate that this quantitative difference in $\rho(B_c)/\rho(0)$ as $n \rightarrow n_c$ in the two systems is probably related to a smoother interface between Si and $SiGe$ and thus, less surface roughness scattering, in our high quality strained Si quantum well. Finally, we note that a similar enhancement of $\rho(B_c)/\rho(0) \sim 1.7$ was also observed in other high quality strained Si QW samples.[21,25]

In summary, in a high electron mobility 2DES realized in the strained Si quantum well, we observe that, with increasing sample quality, the critical density in the 2D metal-insulator transition decreases to a smaller value. Moreover, the measured full spin-polarization magnetic field, B_c, decreases monotonically with n but appears to saturate to a finite value as n approaches zero. The saturation value of the in-plane magnetoresistivity, $\rho(B_c)$, over the zero field resistivity is constant, ~ 1.8, for all the densities ranging from 0.35×10^{11} to 1.45×10^{11} cm^{-2} and,

when plotted versus B_{ip}/B_c, $\rho(B_{ip})/\rho(0)$ collapses onto a single curve.

We would like to thank G. Csáthy for technical help and S.V. Kravchenko for discussion. The work at Princeton was supported by AFOSR under grant No. F49620-02-1-0179 and the NSF DMR0352533. Sandia National Laboratories is a multiprogram laboratory operated by Sandia Corporation, a Lockheed-Martin company, for the U.S. Department of Energy under Contract No. DE-AC04-94AL85000.

Note added: E.H. Hwang and S. Das Sarma have calculated the temperature, density, and parallel magnetic field dependence of low temperature 2D resistivity based on our sample structure and that of Okamoto *et al.* They show in the following theoretical paper that the results observed in this paper can be qualitatively and for some parts of the data semi-quantitatively reproduced using a model where the 2D carriers are scattered by screened random Coulombic impurity centers.

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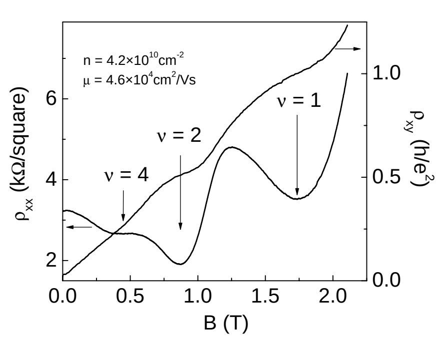

FIG. 1: The magnetoresistivity and the Hall resistance at the density of $n = 0.42 \times 10^{11}$ cm^{-2}. The sample temperature is 0.3 K. The vertical arrows mark the positions of the IQHE states.

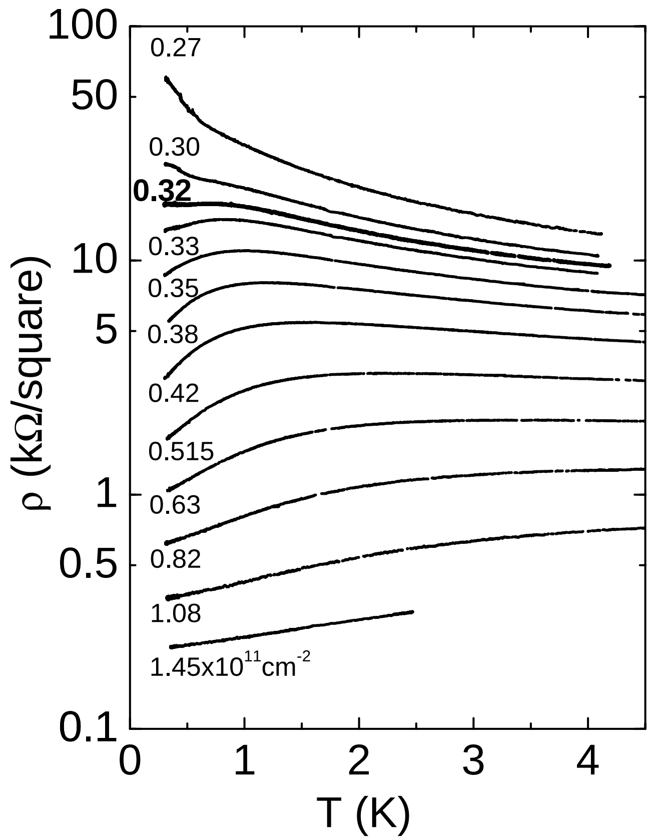

FIG. 2: 2D resistivity ρ as a function of temperature at various densities.

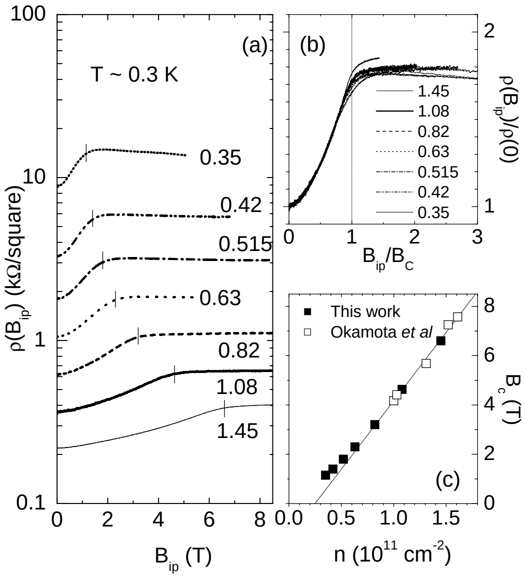

FIG. 3: (a) In-plane magnetoresistivity at a few selected selective 2DES densities. n is in units of 10^{11} cm^{-2}. The positions of full polarization B field are marked by the short lines. (b) The normalized in-plane magnetoresistivity $\rho(B_{ip})/\rho(0)$ vs B_{ip}/B_c. (c) B_c as a function of electron density. Results from Ref. [21] are included. The straight line is a linear fit for densities $n > 0.8 \times 10^{11}$ cm^{-2}.

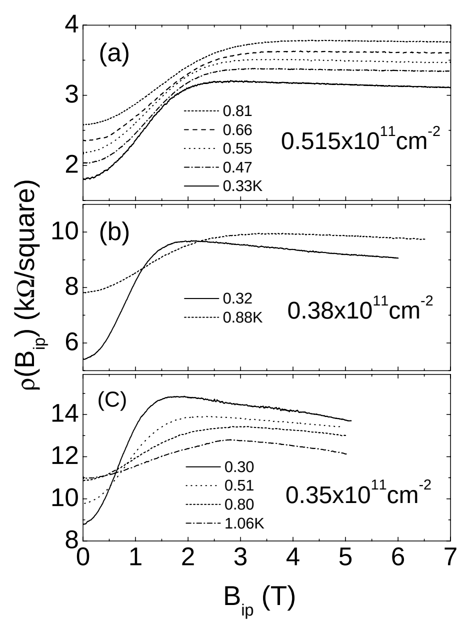

FIG. 4: Temperature dependence of in-plane magnetoresistivity $\rho(B_{ip})$ at three 2DES densities; (a) $n = 0.515 \times 10^{11}$ cm^{-2}, (b) $n = 0.38 \times 10^{11}$ cm^{-2}, and (c) $n = 0.35 \times 10^{11}$ cm^{-2}.